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Three-Axis Tunneling Micro accelerometer Based on Self-Organizing Structures

I.E. Lysenko, M.A. Denisenko, A.S. Isaeva, V.D. Popov

Southern Federal University, Rostov-on-Don, Russian Federation

Abstract: *The paper presents the design and manufacturing technology of a three-axis integral micromechanical tunnel-type accelerometer. The technological features of the controlled self-organization of mechanically stressed semiconductor GaAs / InAs layers for fabricating MEMS sensor structures are considered. The principle of operation of the tunnel accelerometer is presented. The proposed design was modeled and optimized using ANSYS CAD. The obtained simulation results can be used to develop high-tech precision three-axis MEMS linear acceleration sensors.*

Keywords: *microelectromechanical system, linear acceleration sensor, accelerometer, tunnel effect, MEMS.*

I. INTRODUCTION

Microelectromechanical systems (MEMS) are a promising direction in developing modern electronics, which does not lose its relevance. Today, the market is widely represented by multi-axis linear acceleration sensors, two or three devices made on one substrate. To reduce the final product's size and cost and improve manufacturability, it is advisable to develop a direction when such devices are implemented in a single technological cycle. This work describes a three-axis tunneling accelerometer design, which can be made as an independent device. It can be implemented as a sensitive element of a multi-axis sensor. The development of new design and technological solutions and design methods for multi-axis MEMS sensors is an important scientific and technical task, which can ensure the competitiveness of these devices in the world market [1]-[3].

Besides, the creation of tunneling and field emission devices is an urgent direction in developing microelectromechanical accelerometers. Their operation's principle is based on the exponential dependence of the tunneling current flowing between two electrodes (movable and fixed) on the distance between them. It is similar to the principle of operation of a scanning tunneling microscope. A bias voltage is applied to the movable (usually made in the form of a tapered tip) and fixed electrodes of the tunnel contact. When the tip and the stationary electrode are at a distance of several angstroms, a tunneling current occurs. For a registered change in the current strength, it is sufficient to decrease or increase the distance by an amount of 10-3 A. Such sensors have high sensitivity and great potential for miniaturization of the structure, but they require high-precision manufacturing technologies [1].

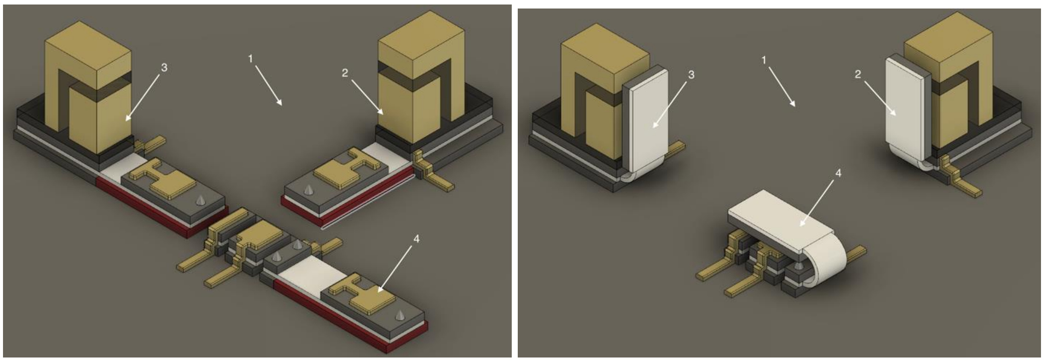
II. PROBLEM

Modern MEMS design techniques and product development allow the use of microsystems in various environments, in a wide range of temperatures, conditions, and pressures, which predetermined their usage even more widely [4]. These systems' manufacturing technology is based on integrating MEMS and a silicon (or another semiconductor) integrated circuit (IC) on a substrate using micro-assembly or an approach where the MEMS part is manufactured together with the IC in a single technological cycle.

Like capacitive ones, tunnel accelerometers work on a similar principle: as a result of acceleration, the inertial mass connected to the moving contact is deflected, which is recorded by the signal processing circuit. One of the important problems in the design of tunneling acceleration sensors is the provision of the required tunneling gap during the device's manufacture and operation. A feedback control scheme is usually used to solve this problem, which allows maintaining a constant gap between the tip of the movable and fixed electrodes [5]. Another important technical challenge is the possibility of implementing multi-axis tunneling sensors in a single technological cycle. The design proposed below has the potential to solve these problems.

III. CONSTRUCTION

A three-axis micro accelerometer consists of three sensors made on one substrate in a single technological cycle: two vertical types and one horizontal type. Sensor elements, each of which is a single-axis accelerometer, can be obtained using the same principles and materials and differ only in the orientation of the moving part and the corresponding contacts, as shown in Fig. 1.



a b

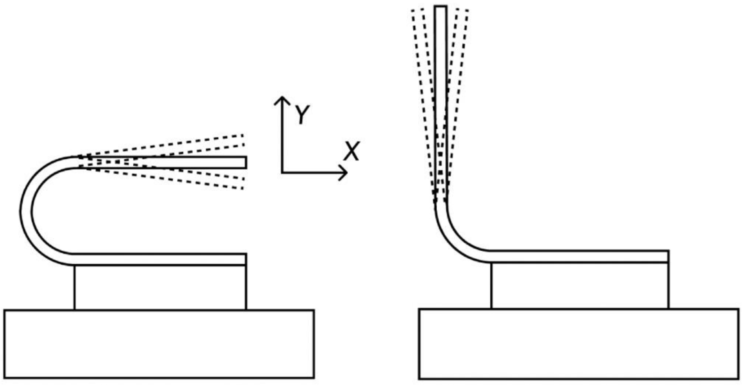
a – before self-assembly; b – after self-assembly
1 - substrate; 2 – Y-axis acceleration sensor; 3 - X-axis acceleration sensor;
4 - Z-axis acceleration sensor

Fig. 1 Design of a three-axis micromechanical tunneling accelerometer

A feature of the proposed design of an integral three-axis MEMS linear acceleration sensor based on the tunnel effect is the use of a self-assembly operation based on controlled self-organization of mechanically stressed semiconductor layers, which allows precise control of the formation of a tunnel contact with a gap of the order of nanometers. This ensures high manufacturability of the construction due to the possibility of its integral manufacturing by group processing methods using standard technological operations, compactness, and the possibility of constructing highly sensitive sensors [6].

The work [4] describes the horizontal structures of tunneling accelerometers. The implementation of these structures is possible using the Prince-technology [7]. It is based on the deformation of the strained layers of the semiconductor hetero film due to the sacrificial layer release (shown in red color in Fig. 1). The degree of deformation of the hetero film depends on how much of the sacrificial layer is etched, which depends on the etching time and the composition of the etchant. By changing these parameters, it is possible to control the process of forming the sensor structure, namely, the elastic suspension and the entire moving part of the structure

Suppose the etching time is sufficient for the console's released a part to become parallel to its fixed part, then under axial loads. In that case, the elastic suspension will show the greatest deviations along the axis perpendicular to the substrate's plane (Y-axis), which is schematically shown in Fig. 2, a. And suppose we reduce the etching time and select it so that the free part of the cantilever becomes orthogonal to the base. In that case, we get a structure in which the cantilever's greatest deviations due to axial loads will be along an axis parallel to the plane of the substrate (X-axis), as shown in Fig. 2 b. Thus, this technology makes it possible to create sensors that are sensitive along different axes.



a b

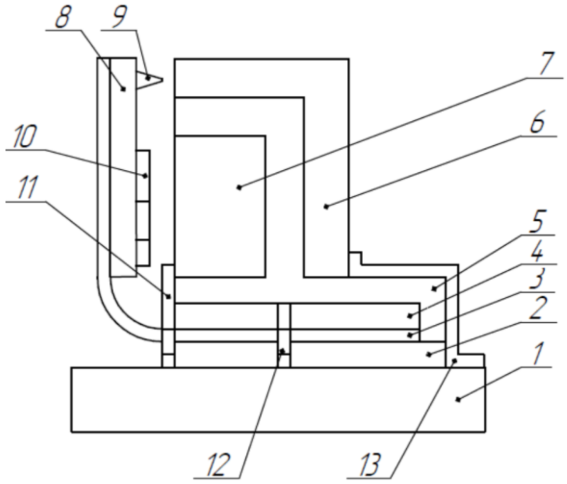
a – horizontal structure with Y-axis sensitivity; b – vertical structure with X-axis sensitivity

Fig. 2 Design sketches of the integral tunneling accelerometers

So the accelerometer providing sensitivity along the axis perpendicular to the substrate plane (Z-axis) has a horizontal structure. It is described in more detail in [8]. Accelerometers sensitive along axes parallel to the substrate plane (X-axis and Y-axis) are identical vertical structures oriented at a 90o angle to each other and shown in Fig. 3.

In each of the three sensors included in the three-axis MEMS accelerometer, a tunnel contact is formed so that its tip is located on the moving part of the structure – a beam with an inertial mass on an elastic suspension. In this case, the opposite contact is stationary relative to the substrate. The gap is several nanometers, which ensures the passage of the tunneling current.

In this case, the tunnel contact is used for high-precision (in comparison with traditional capacitive and piezoelectric elements) registration of changes in the acceleration of an object. In the acceleration along the corresponding axis, the inertial mass is deflected, which changes the distance between the moving and stationary electrodes, and leads to a change in the tunneling current.



1 – silicon substrate; 2 – semi-insulating substrate; 3 – elastic suspension layer; 4 – contact layer; 5 – semi-insulating layer; 6 – fixed tunneling electrode; 7 – fixed electrode of the electrostatic actuator; 8 – inertial mass; 9 – movable tunneling electrode; 10 – movable electrode of the electrostatic actuator; 11 – contact to the fixed electrode of the electrostatic actuator; 12 – contact to the movable electrode; 13 – contact to the fixed tunneling electrode

Fig. 3 Construction of the vertical type accelerometer

IV. MANUFACTURING TECHNOLOGY

The proposed design is carried out using the principles of the technology [7], [9], the essence of which is to grow a heterostructure consisting of mechanically stressed semiconductor layers, for example, GaAs / InAs. During epitaxial growth of these layers, the layers' internal stress arises due to the difference in the periods of the crystal lattices. When free from the substrate (selective etching of the sacrificial layer), interatomic forces tend to decrease/increase the distance between atoms, leading to twisting the structure.

The technological operations used to obtain the described design of a three-axis tunneling accelerometer can be organized so that they can be combined with the technological process of manufacturing integrated circuits based on silicon technologies. It is known that the difference in the Si and GaAs crystal lattices constants is about 4%, which prevents the layers of these materials from being placed on top of each other directly. This problem can be solved through the use of buffer layers. It is specially selected intermediate semiconductor layers that allow a smooth transition from the lattice constant of the silicon substrate to the heterostructure layer's lattice constant.

All the accelerometer's structure layers are obtained by epitaxial growth in a single technological cycle; the movable tunnel contact tip is formed using a focused ion beam.

The operations order is as follows: a GaP buffer layer is grown on a prepared silicon substrate. Then, heterostructure layers are formed. It consists of a sacrificial layer (AlGaAS), as well as InAs and GaAs layers, between which internal mechanical stress arises, which contributes to the self-organization of semiconductor structures and the final accelerometer formation to the subsequent stages. Next, a contact layer of highly doped epitaxial silicon p ++ is grown to connect to the heterolayer. This layer also will act as an inertial mass in the region of the moving contact. A gap of about 1 nm is required for forming a tunnel contact, but it is quite difficult to obtain this gap distance technologically in that structure type. Therefore, it provides an electrostatic actuator. It helps to get a precise setting of the required gap between the movable and fixed contacts due to electrostatic forces. The actuator's metal contact is made of Ti / Pt / Au layers forming an ohmic contact. At the next stage, a movable electrode is formed using a focused ion beam. The insulating layer is SiO2. At the next stage, the stationary electrode of the tunnel contact and the actuator's stationary contact made of Ti / Pt / Au are grown. This materials' composition improves the adhesion to the surface, as the Pt layer is thermodynamically stable and does not allow Ti to migrate to the Au surface. The fixed electrode of the tunnel contact and the actuator's fixed contact are insulated with a SiO2 layer. At this stage, the structure is formed, and it remains to release the moving part of the accelerometer by selective etching of the sacrificial AlGaAs layer. It is possible to twist the structure by a certain angle by choosing the exact etching time. The design of a vertically oriented tunnel micro accelerometer with an indication of the regions' materials is shown in Fig. 4.

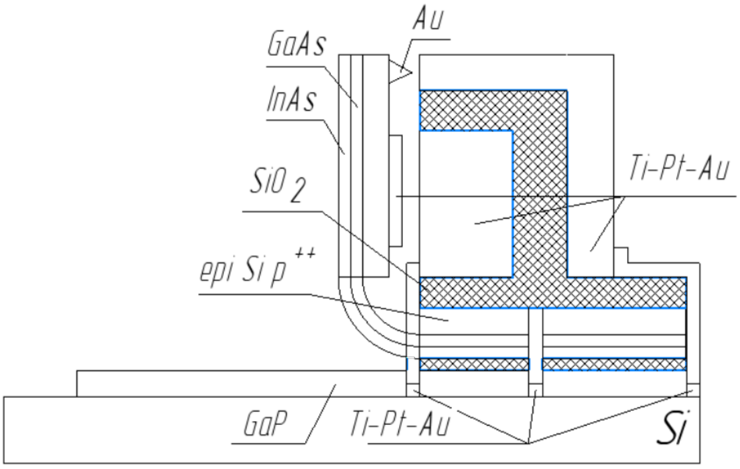


Fig. 4 Materials of the vertical type accelerometer

V. SIMULATION

A three-axis accelerometer model was developed, taking into account the real physical and geometric parameters of the structure in CAD ANSYS 18.0. In this simulation, a static structure analysis was performed, shown in Fig. 5.

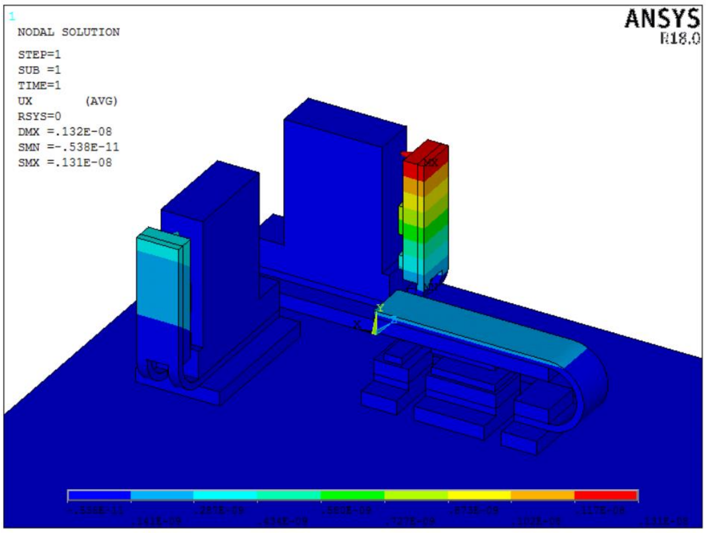


Fig. 5 Simulation results of the developed design of the accelerometer under the influence of acceleration 8g along the X-axis

The numerical results of static analysis are shown in Table I.

TABLE I. ACCELEROMETER SIMULATION RESULTS AT 8G ACCELERATION

Acceleration direction 5g	X-axis offset (m)	Y-axis offset (m)	Z-axis offset (m)
+	$-0.131*10^{-8}$	$-0.190*10^{-8}$	$-0.130*10^{-8}$
-	$0.131*10^{-8}$	$0.190*10^{-8}$	$0.130*10^{-8}$

The mechanical sensitivity was calculated based on the data obtained. As a result of calculations, the following sensitivity values were obtained for each of the axes: SensX = $1.671*10^{-11}$ m., SensY = $2.423*10^{-11}$ m., SensZ = $1.658*10^{-11}$ m. A modal analysis was also carried out to find the frequencies of natural vibrations, which will minimize or eliminate the probabilities of the entire structure entering into resonance. Modal analysis was carried out for the first ten modes from 0 to $10*10^9$ Hz. The values of natural vibration frequencies are shown in Table II.

TABLE II. MODAL ANALYSIS RESULTS

Mode number	Natural vibration frequency (Hz)	Mode number	Natural vibration frequency (Hz)
1	38759.6	6	92623.1
2	47539.5	7	175612.0
3	47782.7	8	362135.0
4	59672.0	9	363186.0
5	92341.8	10	426870.0

Thus, this work describes the developed integral microelectromechanical accelerometer of the tunnel type, which is able to register acceleration along all three axes with high accuracy. The structure model in CAD ANSYS has been developed. Static and modal analysis performed.

ACKNOWLEDGMENTS

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